# Monopoly and the Incentive to Innovate When Adoption Involves Switchover Disruptions

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Arrow (1962) argued that since a monopoly restricts output relative to a competitive industry, it would be less willing to pay a fixed cost to adopt a new technology. We develop a new theory of why a monopolistic industry innovates less. Firms often face major problems in integrating new technologies. In some cases, upon adoption of technology, firms must temporarily reduce output. We call such problems switchover disruptions. A cost of adoption then is the forgone rents on the sales of lost or delayed production, and these opportunity costs are larger the higher the price on those lost units. (JEL F10, L10)

Arrow (1962) postulated that a monopolistic industry would be less innovative than a competitive one. His idea was simple: Since a monopoly restricts output relative to a competitive industry, it would be less willing to pay a fixed cost to adopt a new technology (since there would be fewer units over which to "amortize" the fixed cost). In this paper, we present an alternative theory explaining why a monopolist would be less innovative. We start from the fact that firms often face major problems in integrating new technologies.

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In some cases, upon adoption of technology, firms must temporarily produce substantially below pre-adoption levels. We call such problems *switchover disruptions*. Our idea is also simple: If firms face switchover disruptions, then a cost of adoption is the forgone rents on the sales of those "lost" units, and these opportunity costs are larger the higher the price on those lost units. In particular, higher monopoly power means higher opportunity costs, so less incentive to innovate.

Arrow's idea has been challenged on *theoretical grounds*. A number of critiques have shown that under different (and, *a priori*, as reasonable) assumptions, increases in competition lead to less innovation. Our idea advances the literature since we show that if we add switchover disruptions to a standard (Arrow-type) model, then the critiques of Arrow lose their force: competition again leads to greater adoption. In addition, we show that our model helps explain the accumulating *evidence* that competition leads to greater adoption (whereas the standard Arrow model cannot).

Perhaps the most fundamental critique of Arrow's idea is that, as a matter of theory, when an industry faces increased competition (say, through unilateral tariff reduction), its output may very well fall, and the Arrow logic then implies less innovation (see, e.g., Demsetz 1969 and Yi 1999). Another famous critique is that of Gilbert and Newbery (1982). They switch some of Arrow's assumptions (about who can "bid" on new technology) and show a monopolist now has a greater incentive to adopt than an "outside" rival. Other critiques are discussed below. When we add switchover disruptions to a standard (Arrow-type) model, we show that increases in competition lead to increases in adoption even if output of the industry (and individual firms) falls, and even if we use the Gilbert and Newbery formulation.

Our model also explains the evidence that competition spurs adoption and productivity in a way the Arrow model cannot. In particular, many plant-level studies find that plant-TFP and adoption increase with competition even as plant-output falls significantly.[1] The Arrow model cannot explain rising adoption and TFP in the face of falling output, and in fact predicts the opposite. But our model provides an explanation. Since increased competition leads to lower prices, the opportunity cost of switchover disruption is reduced. Not only is the model consistent with the facts, but in the industry studies noted above, it is clear that it was the reduction in the opportunity costs associated with switchover disruptions that *was* the mechanism by which adoption increased. All this evidence is discussed below.

[1] Below we discuss studies of industries facing increased competition (e.g., Schmitz 2005 and Dunne, Klimek, and Schmitz 2008) and studies of trade liberalization (an early study is Tybout and Westbrook 1995, and there has been an explosion of papers since, many discussed below).

When considering the incentive of a firm to adopt an innovation, Arrow, Gilbert and Newbery, among others, have assumed that new technology can instantaneously and seamlessly be introduced. Adoption does not work that way, and the assumption that it does is not innocuous. Firms often face major problems in integrating new technologies. We will present extensive evidence on such phenomena in the next section.

Following our discussion of switchover disruptions, we present our "baseline" model. The baseline model serves to illustrate the Arrow force for adoption (which we'll call the *Arrow output effect*) and the new force introduced with this paper, the *switchover disruption effect* (again, lower prices mean lower opportunity costs of switchover disruptions). We then introduce extensions to this basic model to address the major critiques of the Arrow idea. These extensions will show that the critiques do eliminate the Arrow output effect, yet the switchover disruption effect remains, and increases in competition can increase adoption.

In our model, there will be an incumbent firm that faces a group of rival firms. The incumbent firm will initially have a cost advantage over its rivals, indexed by the parameter $\tau$. One interpretation is that the incumbent is a domestic firm and the rivals are foreign firms. Foreign firms must incur an additional cost of $\tau$ per unit (above and beyond production costs) to serve the local market, where $\tau$ could be a tariff or a transportation cost. A new technology will become available. If a firm adopts the technology, its costs may initially increase (if there is switchover disruption), and it may initially lose sales. We will consider how the incentives to adopt the technology vary as the market power or tariff parameter $\tau$ is changed. This incumbent-versus-rivals structure is similar to the approach in Gilbert and Newbery and Reinganum (1983).

The incentive-to-innovate literature has expanded to consider a wide range of oligopoly models (Schmutzler 2007 is a recent review; see also references in Vives 2008). But all this literature, as far as we know, has assumed that firms can instantaneously and seamlessly introduce new technologies.[2] Switchover disruptions are not considered.

We should note that there have been several earlier efforts to make more relevant the Arrow result that more competition leads to greater innovation. Rather than pursuing switchover disruptions, these analyses have often focused on issues such as managerial incentives or patent races. Schmidt (1997) and Raith (2003) take the managerial incentives route. In Schmidt, it is the fear of bankruptcy that drives management, whereas in Raith it

[2] In some papers there is uncertainty regarding how long it may take to develop an innovation. Similarly, there are models in which there is uncertainty as to how much better an innovation will be. But once an innovation is developed, it can be seamlessly adopted.

is the increase in firm-level output following free entry. Aghion et al. (2005) show that when there is a "neck and neck" patent race between two rival firms, the incentive to innovate is extremely high: this captures the old Schumpeterian (1911) idea that competitive firms innovate in order to capture a future monopoly. We should also mention Segal and Whinston (2007), who show that antitrust policies can have ambiguous effects on innovation by making it more profitable for entrants to innovate, but less profitable for incumbents. In Vives (2008), increasing the number of firms lowers innovation, but if the measure of competition is product substitutability, then innovation is increased.

An old saying is, "If you have a good thing going, don't rock the boat." Here, a firm with a lucrative monopoly may decide not to adopt a technology that, in the short run, disturbs its lucrative position. Another old saying is, "If you have nothing to lose, swing for the fences." Recent papers have attempted to capture this idea in models where a firm's R&D investment is a choice of variance in outcomes (see, e.g., Anderson and Cabral 2007). The point here is to show that firms that are far behind may decide to choose high variance R&D programs. Again, switchover disruptions are not considered.

Having switchover disruptions in economic models is by no means a new idea. There is a large literature in which switchover disruptions play an important role, for example, in Chari and Hopenhayn (1991), Jovanovic and Nyarko (1996), Parente (1994), Klenow (1998), and Schivardi and Schneider (2008). A major focus of these papers has been to see how switchover disruption influences investment. In that sense, they are close cousins to this paper. However, the papers have not considered how switchover disruptions in adopting technology might change the relationship between market power and the incentive to innovate.

## I. Motivating Switchover Disruptions

We use this section to motivate introducing switchover disruptions into the incentive-to-innovate literature. In particular, this section provides evidence that when firms adopt new technologies, they often experience an initial increase in costs (or decrease in productivity). In fact, of course, some new technologies never succeed.

One note before we begin. If new technologies can yield higher costs than old ones, firms would obviously run pilot projects to learn whether new technologies were better. Firms obviously do this. But as argued and seen below, for many technologies testing can reduce uncertainty only a modest amount. Pilot projects can often test only one dimension of the technology in isolation from others. To know whether a technology works can be learned only by turning on all the systems at once. And then the system must be run for substantial periods of time before the productivity of the technology is learned. In this paper, we do not delve into why technology has this feature, but we do explore its consequences.[3]

Let us start by presenting evidence on switchover disruptions faced by three well-known firms. We then turn to more formal studies, looking at switchover costs in manufacturing, in supply chains, and in organizational innovation in general.

**A. Switchover Costs in Specific Adoption Episodes**

When discussing evidence, we think it's productive to begin with concrete examples of switchover disruptions. We will give three such cases, though a much larger list is easy to compile. The specific episodes are not meant to be a "test" of our model (i.e., one should not be asking whether the firms have lots of, or little, market power), but simply evidence that disruption is important. A more productive way to test the idea is to look at cases where firms faced large *changes* in market power, and ask how this *changed* their adoption decisions. (We will address this a bit later.)

*Boeing.* In building the 787 Dreamliner, Boeing chose a new technology, one that involved its suppliers assembling more of the parts off-site than usual and then shipping to Boeing for final assembly. Such a process had been pursued successfully in other manufacturing industries. However, Boeing has faced major problems—switchover disruptions—in implementing the technology. Suppliers have been slow to send assembled parts, spurring Boeing to request suppliers to ship unassembled work to them. But "Boeing has ended up with a pile of parts and wires, and lots of questions about how they all fit together, not unlike a frustrating Christmas morning at home." With ever-growing delays in promised delivery dates, Boeing may lose substantial business to Airbus. It's clear that it is taking Boeing a substantial period of time to learn whether the new system is better than the old.[4]

*General Motors.* In the 1980s, after suffering large losses in market share to Japanese producers, General Motors (GM) invested heavily in automation and robots in order to stem losses in market share. But when factories reopened with their new automation systems, major production problems arose. Robots often did not run. When they did, they "often began dismembering each other, smashing cars, spraying paint everywhere and even fitting the wrong equipment." GM found that "technologies that worked well in isolated pilot projects [weren't] easily coordinated in the real world of high-volume manufacturing." Many of the

[3] A related issue is why a firm does not immediately switch back to its old technology if costs initially increase with adoption. Again, it is not possible to do so in many (all?) cases, as is also seen below.

[4] See coverage in the *New York Times*, January 16, 2008, "Boeing Is Expected to Disclose Further Delays," and January 17, 2008, "Supplier Woes Lead to New Delay of Boeing 787."

factories were able to produce only a small share of their rated capacity for months and months.[5]

*United Airlines.* When a new Denver airport was built in the mid-1990s, United Airlines and the city decided to install a highly automated baggage handling system. Major switchover disruptions occurred. The system "immediately became known for its ability to mangle and misplace a good portion of everything that wandered into its path." A year after opening, United sued the builder of the system, claiming that it "performed miserably." For the first decade of operation, United used only a stripped-down version of the system. Finally, United decided to turn the system off in 2005.[6]

**B. Switchover Costs in Manufacturing**

*U.S. Apparel Manufacturing.* Dunlap and Weil (1996) studied the adoption of new technology, modular production systems, in U.S. apparel manufacturing. Of the firms they studied (accounting for about 30 percent of industry shipments), about 40 percent had adopted the technology at some point. Of those that adopted, about 50 percent abandoned the technology. The overwhelming reason given for dropping the innovation was that it lowered labor productivity.

*Japanese Steel Manufacturing.* Nakamura and Ohashi (2005) examine the experience of Japanese steel manufacturers when they shifted from the open-hearth furnace (OHF) to the basic oxygen furnace (BOF) in the 1950s and 1960s. They found that plants adopting the new technology experienced significant declines in productivity (TFP) at the time of adoption. They estimated a 14 percent drop in productivity initially and that it was three years before the BOF productivity approached the level of the old OHF productivity.

*U.S. Steel Manufacturing.* Ichniowski and Shaw (1995) studied the adoption of new technology in U.S. steel finishing lines. They looked at the adoption of management innovations, in particular, human resource management (HRM) innovations. They view "the adoption of an innovative HRM system as an investment decision analogous to a decision to invest in physical capital" (p. 20). We share this view. One of the costs of adoption that they emphasized was the uncertainty in how the technology would perform after adoption. A

[5] For coverage see "When GM's Robots Ran Amok," *The Economist*, August 10, 1991; "Tricky Auto Makers Discover 'Factory of the Future' Is Headache Just Now," *Wall Street Journal*, May 13, 1986; "Detroit Stumbles on Its Way to the Future," *Business Week*, June 16, 1986.

[6] United's lease (in 2002) requires it to pay the city $60 million a year for the automated system (for 25 years). Hence, United must swallow this loss. However, United will reduce its operating costs by returning to manual baggage handling and expects to save $12 million a year on these costs. For coverage of this story, see "United Abandons Denver Baggage System," Associated Press, June 7, 2005; and "Denver Airport Saw the Future. It Didn't Work," *New York Times*, August 27, 2005.

large part of the uncertainty arose from the potential resistance to the new technology (by line workers, union officials, and managers).[7] We share this view that one possible source of switchover disruption is resistance to innovation.

*General Manufacturing.* Some researchers have looked at the productivity experience of manufacturing plants after they have undergone a major surge in investment. Using these surges as proxies for adoption of technology, they have found that productivity has initially fallen after adoption. Studies include Huggett and Ospina (2001), who looked at what happened to trend productivity growth after adoption, and Sakellaris (2004), who looked at the impact on levels of productivity.

### C. Switchover Costs in Supply-Chain Management

Changes in supply-chain systems will almost certainly cause switchover disruptions. There is no way of knowing if a system is better without trying it. Boeing is now in the process of such learning. A thriving literature in operations research and management has studied the consequences of supply-chain disruptions, brought on by glitches in moving to new technology and other sources of disruption. The literature has found large losses in productivity and share value as a result of glitches (see, e.g., Hendricks and Singhal 2003, 2005 and references therein).

### D. Switchover Costs in Organizational Changes

Organizational changes will almost certainly cause switchover disruptions. A new organizational structure might be better or worse, but there is really no way of knowing without the entire organization trying it. If it is worse, there is no way to switch back to the old organization overnight if at all. We will discuss a few areas in which firms attempt to improve their organizations (and lower their production costs).

*Work Rule Changes.* A subset of organizational innovation involves firms changing the work rules of a union. Here it may be clear that a new set of work rules (e.g., more flexible ones) would lead to much lower costs. Yet introducing the changes might lead to a union strike and a considerable period of downtime. Indeed, during many episodes firms were shut down for long periods before being able to change the work rules, and in some instances, were not able to change them at all.

*A Potpourri of Workplace Changes.* To finish this section, we'll simply list some examples of other switchover disruption discussed in the organization literature. Marketing

[7] According to Ichniowski and Shaw, "Our interviews highlighted many cases where attempts to introduce new [technology] were undermined by low levels of trust between labor and management" (p. 51).

departments have faced disruptions introducing sales force automation technology (see, e.g., Speier and Venkatesh 2002). Human resource departments have faced disruptions in introducing new workplace compensation schemes (see, e.g., Beer and Cannon 2004). And, of course, introducing new information technology systems often leads to significant disruptions (see, e.g., Ginzberg 1981). Lastly, obviously switchover disruptions take place as CEOs are changed.

## II. Baseline Model

Consider a homogeneous products industry in which production takes place over a unit time interval $t \in [0, 1]$. There is one firm, the *incumbent*, that initially has a cost advantage over its *rivals*. Let $c^\circ$ denote the initial marginal cost of the incumbent. The rival firms (assume there are two or more of them) each have marginal cost equal to $c^\circ + \tau$, for $\tau \geq 0$. The parameter $\tau$ governs the degree of market power that the incumbent has over the rivals, and it will be the key element in our comparative statics analysis.

One interpretation of the $\tau$ parameter is that the incumbent is a domestic firm and the rivals are foreign firms. All firms have the same production cost $c^\circ$, but the foreign firms must incur an additional cost of $\tau$ per unit, which could be a tariff or a transportation cost.

We assume *Bertrand competition*, that is, that firms compete in price.

### A. New Technology

At time $t = 0$, a *new technology* becomes available. If the new technology is adopted at time $t = 0$, then marginal cost at time $t$ equals $c_t = f(t)$. We assume that marginal cost falls over time in a continuous and strictly decreasing fashion, $f'(t) < 0$. Let $\bar{c} = f(0)$ be the high initial cost and $\underline{c} = f(1)$ be the low cost ultimately attained, $\underline{c} < \bar{c}$.

We assume that $\underline{c} < c^\circ$ so that ultimately the new technology is better than the original. The key innovation in our analysis is to allow for the possibility that $\bar{c} > c^\circ$. When that happens, we say there is a *switchover disruption* at the initial point of adoption. Figure 1 illustrates an example. We can think of there being some prior period $t \in [-1, 0)$ over which cost was constant at $c^\circ$. When the new technology is adopted, marginal cost goes up initially but eventually is lower.

### B. Demand Structure

The quantity demanded (at each $t \in [0, 1]$) in the industry at price $p$ is $Q^D(p)$. We assume that demand is *weakly inelastic*, that is,

(1) $Rev(p) = Q^D(p)p$ is weakly increasing in $p$.

This assumption simplifies our calculations because it implies that the incumbent will limit price at the rival's cost.

### C. Who Can Adopt?

The final issue to be determined is: Who gets to adopt the new technology? Our baseline approach follows Arrow (1962). Here the incumbent alone has a choice to adopt. The incumbent can pay a fixed cost $F \geq 0$ to adopt the new technology or pay no fixed cost and use the original technology instead. If the incumbent does adopt, the rivals can be excluded and the rivals' marginal cost remains at $c^\circ + \tau$. The essence of the Arrow setup is that the incumbent is choosing between having the new technology for itself and no one having it.[8]

## III. Monopoly and the Incentive to Innovate

This section provides our baseline analysis of how the incentive to innovate depends on monopoly power $\tau$. The analysis highlights two forces for how a decrease in $\tau$ increases incentives to innovate. The first is the familiar Arrow output effect. The second is the new effect, the switchover disruption effect, which we introduce with this paper.

In this baseline model, recall that only the incumbent has the option to adopt. Consider the incumbent's decision at $t = 0$ (if it does not adopt at $t = 0$, it would never adopt). If the incumbent does not innovate, the equilibrium price from Bertrand competition is the limit price $p^\circ = c^\circ + \tau$. This yields a profit margin of $p^\circ - c^\circ = \tau$ per unit sold. The incumbent's sales will be $Q^\circ = Q^D(c^\circ + \tau)$ at each instant along the unit time interval and the profit flow $\tau Q^D(c^\circ + \tau)$.

In calculating the present value of profits, it will be convenient in the analysis to integrate over the cost path $c(t)$ rather than over $t$. For the case where $f$ is continuous and strictly decreasing, let $G(c)$ denote how much time remains when marginal cost equals $c$, for $c \in [\underline{c}, \bar{c}]$. That is, $G(c)$ is the value of $x$ solving $f(1 - x) = c$. Thus $G(\bar{c}) = 1$ and $G(\underline{c}) = 0$, and $0 < G(c) < 1$ for $\underline{c} < c < \bar{c}$. The cumulative distribution function over marginal cost during the time interval is $G(\cdot)$ and let $g(c) = G'(c)$ be the density of marginal cost. Finally, letting

[8] In many cases, this setup is clearly appropriate. When a firm decides whether to adopt a new supply system, a new human resource system, and so on, it is the only firm that has a say in the decision.

$\rho$ be the discount rate, define $h(c)$ as

$$(2) \quad h(c) \equiv e^{-\rho(1-G(c))} g(c).$$

This will show up in the formulas below as the weight on profits when cost is $c$. The first term takes discounting into account, since the time is $t = 1 - G(c)$ when cost is $c$. The second term takes the density of $c$ into account.[9]

The present value of the profit flow $\tau Q^D(c^\circ + \tau)$ of not adopting the new technology then equals (as a function of $\tau$)

$$(3) \quad v^\circ(\tau) = \tau Q^D(c^\circ + \tau) \int_{\underline{c}}^{\bar{c}} h(c)dc.$$

If instead the incumbent adopts, it obtains a cost path that starts with $\bar{c}$ and monotonically decreases to $\underline{c}$. If the initial cost $\bar{c}$ is above $c^\circ + \tau$, it drops out of the market until its cost falls to the limit price. Beyond this point, the incumbent's cost $c$ is below $c^\circ + \tau$, and it sets the limit price $p = c^\circ + \tau$.[10] The present value to the incumbent from adoption, netting out the fixed cost of adoption $F$, then equals

$$(4) \quad v(\tau) = Q^D(c^\circ + \tau) \int_{\underline{c}}^{\min\{\bar{c}, c^\circ + \tau\}} h(c) \left[c^\circ + \tau - c\right] dc - F.$$

The net return to adoption is the difference between $v$ and $v^\circ$,

$$(5) \quad W(\tau) = Q^D(c^\circ + \tau) \left[ \int_{\underline{c}}^{\min\{\bar{c}, c^\circ + \tau\}} h(c) \left[c^\circ + \tau - c\right] dc - \tau \int_{\underline{c}}^{\bar{c}} h(c)dc \right] - F.$$

[9] As a help to the reader regarding notation, consider the case if there was no discounting. Then since $h(c)$ is the "weight" at each $c$, the integral of $h(c)$ over costs equals one, that is, $\int_{\underline{c}}^{\bar{c}} h(c)dc = 1$. With discounting, we have that $\int_{\underline{c}}^{\bar{c}} h(c)dc = \int_0^1 e^{-\rho t}dt$.

[10] If the initial cost $\bar{c}$ is below $c^\circ + \tau$, the incumbent sets the limit price over the entire interval.

Differentiating the net return to adoption with respect to the cost advantage $\tau$ yields

$$(6) \quad \frac{dW(\tau)}{d\tau} = \frac{dQ^D}{dp}\left[\int_{\underline{c}}^{\min\{\bar{c},c^\circ+\tau\}} h(c)\left[c^\circ+\tau-c\right]dc - \tau\int_{\underline{c}}^{\bar{c}} h(c)dc\right] -Q^D\int_{\min\{\bar{c},c^\circ+\tau\}}^{\bar{c}} h(c)dc.$$

The slope is the sum of two terms. The first is the *Arrow output effect.* The second is the *switchover disruption effect.* We next state Proposition 1, which provides sufficient conditions under which decreases in market power $\tau$ increase innovation.

*Proposition 1.* At any $\tau$ where the return to adoption is positive, $W(\tau) > 0$, the slope is weakly negative, $W'(\tau) \leq 0$, and is strictly negative if either (i) $\frac{\partial Q^D}{\partial p}(c^\circ+\tau) < 0$ (strict downward-sloping demand) or (ii) $\bar{c} > c^\circ + \tau$ (significant switchover disruption).
*Proof.* If $W(\tau) > 0$, since $F \geq 0$, it must be the case that

$$(7) \quad \left[\int_{\underline{c}}^{\min\{\bar{c},c^\circ+\tau\}} h(c)\left[c^\circ+\tau-c\right]dc - \tau\int_{\underline{c}}^{\bar{c}} h(c)dc\right] > 0.$$

This says that, on average, profitability per sale increases. Plugging (7) into the slope formula (6) immediately implies $W'(\tau) \leq 0$, and the claims about the strict inequality follow as well.

Proposition 1 says that if the new technology is worth adopting ($W(\tau) > 0$), then an increase in $\tau$ decreases the return to adoption ($W'(\tau) < 0$).[11] This implies that the return to adoption takes the form of a cutoff rule $\hat{\tau}$, where the incumbent adopts if $\tau < \hat{\tau}$ and does not adopt if $\tau > \hat{\tau}$. (Let $\hat{\tau} = 0$ in cases where it never adopts and $\hat{\tau} = \infty$ in cases where it always adopts.) If we think of $F$ as a random variable with some distribution, then the cutoff $\hat{\tau}$ will decrease in $F$. Hence adoption is more likely the lower is $\tau$.

To get a clearer picture of the first term of $\frac{dW}{d\tau}$ in (6), the Arrow output effect, it is helpful to rewrite this term when $\bar{c} \leq c^\circ + \tau$. In this case, it reduces to

$$\textit{Arrow output effect:}\ \frac{dQ^D}{dp}\int_{\underline{c}}^{\bar{c}} h(c)\left[c^\circ - c\right]dc, \text{ if } \bar{c} \leq c^\circ + \tau.$$

It equals the average (marginal) cost reduction from the new technology times the change in market quantity from higher market power. The big idea is that there exist scale economies

[11] We note that we can extend Proposition 1 to the case of elastic demand for the special case where the cost path takes on two values, $f(t) = \bar{c}$ for $t < \hat{t}$ and $f(t) = \underline{c}$.

from adoption. There is one fixed cost, and cost savings per unit are applied to multiple production units. The greater the market power through $\tau$, the lower the production volume, and the fewer units over which to average the expense of the fixed cost. In short, an incumbent with high market power does not sell many units and so is less inclined to pay a given fixed cost to lower marginal coat. This well-known idea from Arrow is also called the *replacement effect* (see, e.g., Tirole 1988 on this terminology).

To get a clearer picture of the second term of $\frac{dW}{d\tau}$ in (6), it is helpful to rewrite this term when $\bar{c} > c^{\circ} + \tau$. In this case, the term reduces to

$$(8) \quad \textit{switchover disruption effect:} \; -Q^D \int_{c^{\circ}+\tau}^{\bar{c}} h(c)dc, \text{ if } \bar{c} > c^{\circ} + \tau.$$

This equals (minus) the present-value-weighted total time of the switchover disruption period times the volume of lost sales. If monopoly power $\tau$ increases by one dollar, this is the additional profit forgone during the switchover disruption.

This effect can be seen in Figure 2. For this figure, we assume that demand is perfectly inelastic. In the figure, there are two identical panels, except that the switchover disruption in the left panel is "small" (that is, $c^{\circ} + \tau > \bar{c}$) and is "large" in the right panel. The dark shaded areas in both panels represent the total profits that are lost as a result of the disruption, and the light shaded areas are the profits that are gained when costs fall below original costs. In the left panel, when an incumbent adopts, it does not lose any sales, and the switchover disruption terms drop to zero. Increases in $\tau$ in this case do not increase the size of the dark shaded area and have no effect on adoption decisions. In the right panel, when an incumbent adopts it loses sales. Now, increases in $\tau$ increase the size of the dark shaded area. The opportunity cost of the forgone sales during the disruption period is greater, decreasing the incentive to innovate. This is the term (8).

## IV. The First Extension: Declining Output

Arrow's view that competition leads to greater innovation has been challenged on *theoretical grounds*. Perhaps the most fundamental critique is that, as a matter of theory, when an industry faces increased competition (say, through unilateral tariff reduction), its output may very well fall, and the Arrow logic then implies less innovation. In this section we show that if the baseline model above is extended to allow for decreasing output, then competition still leads to increased innovation (under some conditions, of course).

To begin addressing this issue, consider what happens if demand $Q^D(p)$ is perfectly inelastic so that $dQ^D/dp = 0$. The Arrow output term in the slope (6) reduces to zero. If there is no significant switchover disruption ($\bar{c} \leq c^\circ + \tau$), the second term is zero as well, so a change in market power $\tau$ has no impact on the incentive to innovate. However, if there is significant switchover disruption, $\bar{c} > c^\circ + \tau$, the second term is strictly negative, and our result that the incentives to innovate decline with $\tau$ goes through.[12]

A decrease in monopoly power $\tau$ might *decrease* the incumbent's output. For example, suppose the industry here is an intermediate good industry in the manufacturing sector. Suppose it sells its output to other domestic manufacturing firms. Now imagine that there is a unilateral tariff reduction across *all* manufacturing industries. The tariff reduction will lead to a price reduction in the intermediate good industry, but some of its local market may simply disappear. Some of its upstream industries (or firms) may be eliminated by imports. Then, even as the intermediate industry's price falls, industry output falls. This was the case in the U.S. iron ore industry in the 1980s. Foreign competition led the domestic industry to significantly reduce its price, yet the sales of the industry also fell significantly (since U.S. steel producers lost sales to foreign steel producers).

We could extend the baseline model along the lines suggested in the paragraph above (distinguishing intermediate manufactures, etc.) But to keep things simple, we'll assume a reduced form relationship between industry demand and the tariff rate; that is, we'll assume demand is $Q^D(p, \tau)$. Holding $p$ fixed, quantity demanded falls as $\tau$ falls. Again, one interpretation is that $\tau$ is a manufacturing-wide tariff, and its reduction means a smaller market for this intermediate industry.

In terms of the analysis above, in equation (5), we replace $Q^D(c^\circ + \tau)$ with $Q^D(c^\circ + \tau, \tau)$. To look at the impact of an increase in $\tau$ on the incentive to innovate, we need only replace $dQ^D/dp$ in first term of the slope (6) with $dQ^D/d\tau$, where of course this latter derivative is a "total derivative." If the total derivative $dQ^D/d\tau < 0$, everything is qualitatively the same. But if $dQ^D/d\tau > 0$, then the sign of the first term in (6) (the Arrow output effect) flips. In particular, if there is no significant switchover disruption so that $\bar{c} \leq c^\circ + \tau$, the incentive to innovate $W(\tau)$ *strictly increases* with market power $\tau$, as opposed to decreasing. This is the "declining-output" critique. However, if there is significant switchover disruption, there are two offsetting effects. If the output effect from $dQ^D/d\tau$ is not too big, the switchover disruption effect will dominate, and an increase in $\tau$ will decrease incentives to innovate.

Notice that switchover disruptions are needed to explain how increased competition can lead to increased innovation in the face of output declines. This is a feature of empirical

[12] The reader will notice that this situation was covered by Proposition 1.

studies, that is, increased adoption in the face of falling output, that has remained a puzzle until now.

The evidence comes primarily from two sources, studies of specific industries that have undergone a dramatic increase in competition, and from unilateral trade liberalizations. The industry studies, and trade liberalization studies, uniformly show that as competition increases, productivity (e.g., TFP) at the establishment level increases.[13]

What happened to the size of the industry and individual establishments as competition increased (and spurred productivity)? Here, too, the studies speak with one voice: competition reduced industry and establishment size.

Consider first the study of specific industries. When competition hit the U.S. iron ore industry, its output fell in half. It was only after more than a decade that industry output returned to a level close to its pre-competition level. The same was true at the establishment (i.e., mine) level (Schmitz 2005). In cement, foreign competition reduced industry output by 30 percent in the early 1980s, and output did not reach its pre-competition level until the mid-1990s. In U.S. transportation, rail competition greatly reduced water shipments.

In the studies of (unilateral) trade liberalization's impact on productivity mentioned above, not all studies looked at the consequences of liberalization on industry (and establishment) size. But among those that did, establishment size falls. Hay (2001) shows that following unilateral trade liberalization in Brazil, its large manufacturing firms lost significant market share to foreign firms, had their profits fall sharply, yet increased their efficiency dramatically. Trefler (2004) finds that reductions in Canadian tariffs against the United States led to reductions in gross output per plant in Canada.[14] Bloom, Draca, and Van Reenen (2008) show that (European) plants facing the greatest increase in imports from China had the greatest increase in technology adoption (and had the greatest reduction in size measured by employment).[15]

It is hard to understand these findings in Arrow-type models—the findings that as a

[13]Studies looking at specific industries, in addition to those discussed below, include Bridgman, Gomes, and Teixeira (2008). Studies of trade liberalization's impact on plant productivity have grown significantly in the last decade. The studies, which uniformly find a positive impact on plant productivity, include Tybout and Westbrook (1995) (Mexico), Hay (2001) (Brazil), Pavcnik (2002) (Chile), Muendler (2004) (Brazil), Topalova (2004) (India), Trefler (2004) (Canada), Bernard, Jensen, and Schott (2006) (U.S.), Amiti and Konings (2007) (Indonesia), De Loecker (2007), Fernandes (2007) (Columbia), and Bloom, Draca, and Van Reenen (2008) (OECD).

[14]Trefler's Table 5 shows the negative impact of tariff reductions on size.

[15]There is another literature that looks at the impact of trade liberalization on average firm and plant size (but does not focus on productivity). An important paper in this literature is Head and Ries (1999). Summarizing this literature, Tybout (2006) says, "The finding that foreign competition is associated with smaller firms in import competing industries seems robust."

plant shrinks from foreign competition, its TFP (and technology adoption) increases. Our theory here provides an interpretation of these findings. As competition lowered price in these industries, it reduced the opportunity costs of lost sales if adopters ran into switchover disruptions. Not only is the argument consistent with the facts, but in the industry studies noted above, it's clear this *was* the mechanism by which adoption increased.

Consider, for example, the U.S. iron ore industry. For nearly a century, until the early 1980s, the U.S. and Canadian iron ore industries were the exclusive suppliers to steel plants in the Midwest manufacturing belt (e.g., Chicago and Cleveland). At that time they faced a significant increase in competition in these markets. In response, they adopted a technology that led to a surge in productivity. The technology was a change in organization, in particular, a change in work rules (see, for example, Galdon-Sanchez and Schmitz 2002 and Schmitz 2005). The firms could have instituted these changes prior to the reduction in market power, but there would have been a switchover disruption, namely, a likely protracted strike by the union. With significant market power, and high iron ore prices, the opportunity costs of lost sales were too high. With the surge in competition, prices and rents fell dramatically. The opportunity costs of a protracted strike were now much lower, and the firms decided to pursue new work rules.[16] Similar developments occurred in the U.S. cement industry (Dunne, Klimek, and Schmitz 2008) and U.S. transportation industries (Holmes and Schmitz 2001).[17]

To close this section, let's return to another *theoretical* critique of the Arrow model, one that is related to the *declining-output* issue: What happens if the new technology reduces fixed costs, leaving marginal cost alone? Suppose there is a flow fixed cost $\phi$ that must be paid each instant when output is positive, but not paid at zero output. Suppose initially, the cost is $\phi^{\circ}$, but if the new technology is adopted, the fixed cost goes from $\bar{\phi}$ at the beginning to $\underline{\phi} < \bar{\phi}$ in the end. If $\bar{\phi}$ is high enough, the incumbent will shut down initially to avoid paying it. It is straightforward to see how we could redo the analysis of the previous section with this setup. The Arrow output effect would, of course, disappear because it depends on production volume, which is irrelevant with a fixed cost. However, the switchover disruption term remains, and competition again leads to adoption (if the switchover costs are large enough).

[16] It's also quite possible that the firms thought the possibility of a strike, and its duration if it did happen, had fallen as well. But our model predicts this, too, is a force for technology adoption.

[17] The studies above looked at how changes in competition led to changes in technology adoption. Other studies have looked cross sectionally, for example, Syverson (2004). Other proxies for changes in competition include regulatory restructuring (e.g., see Fabrizio, Rose, and Wolfram 2007) and changes in cartel laws (see, e.g., Symeonidis 2008).

## V. The Second Extension: Gilbert and Newbery

A famous critique of Arrow is Gilbert and Newbery's (1982). They change the model setup and allow the rivals to also bid for the new technology. They show the monopolist has the greatest willingness to pay and that it increases in $\tau$. In this section we show that if the baseline model above is extended to allow for the rivals to bid, then competition still leads to increased innovation (under some conditions, of course).

Formally, we assume an outside researcher can sell exclusive rights to use the technology to the incumbent or one of the rivals. If a rival uses the new technology, it still needs to pay the friction $\tau$, in addition to the marginal production cost. Assume that the outside researcher can commit to an auction technology that extracts the full surplus from the bidder with the valuation. In the analysis, we need to determine: Who has the highest valuation, the incumbent or a rival, and how much is the high bidder willing to pay? We examine how the answers to these questions depend on $\tau$.

We proceed by first working things out when there is no switchover disruption. We then determine how things change when we put switchover disruption into the model. To highlight the role of switchover disruption, we zero out the Arrow output effect by assuming demand is *perfectly inelastic* at unit demand, i.e., $Q^D(p) = 1$ for all $p$.

We begin with some additional notation. As in the previous section, let $v$ denote the present value to the incumbent when it acquires the new technology. Now let $u$ denote the present value to the *incumbent* when a *rival* obtains the new technology. Finally, let $r$ be the present value to a *rival* when it acquires the new technology.

### A. Adoption with No Switchover Disruption

Suppose there is no switchover disruption, $\bar{c} \leq c^{\circ}$. Define value $v^{No\_SD}$ to be the value to the *incumbent* of acquiring the rights to the new technology. This is just the formula (4) in the previous subsection with $Q^D(c^{\circ} + \tau) = 1$ and $\min\{\bar{c}, c^{\circ} + \tau\} = \bar{c}$. The value $u^{No\_SD}$ to the incumbent if the rights are acquired by a rival firm is

$$(9) \qquad u^{No\_SD} = \int_{\max\{c^{\circ}-\tau, \underline{c}\}}^{\max\{\bar{c}, c^{\circ}-\tau\}} h(c)\,[c + \tau - c^{\circ}]\,dc.$$

By using the max operator in (9) above, we subsume different cases. If $\max\{\bar{c}, c^{\circ} - \tau\} = c^{\circ} - \tau$ (equivalently $c^{\circ} \geq \bar{c} + \tau$), the incumbent is immediately undercut at the point of adoption by a rival and the integral above is 0 (limits of integration are $c^{\circ} - \tau$ and $c^{\circ} - \tau$). If alternatively $c^{\circ} < \bar{c} + \tau$, the incumbent is at least initially the low cost producer, taking into account $\tau$, but it will have to set the price to $\bar{c}+\tau$ to match the adopting rival.

Finally, the value to a *rival* if the rival acquires the new technology rights is

$$r^{No\_SD} = \int_{\min\{\underline{c},c^{\circ}-\tau\}}^{\min\{\bar{c},c^{\circ}-\tau\}} h(c)\left[c^{\circ}-\tau-c\right]dc,$$

where, again, by using the min operator above we subsume different cases.

The maximum willingness to pay for the rights to the new innovation is

$$\begin{aligned} W^{No\_SD} &= \max\left\{v^{No\_SD}-u^{No\_SD}, r^{No\_SD}\right\} \\ &= \max\left\{\begin{array}{c} \int_{\underline{c}}^{\bar{c}} h(c)\left[c^{\circ}+\tau-c\right]dc - \int_{\max\{c^{\circ}-\tau,\underline{c}\}}^{\max\{\bar{c},c^{\circ}-\tau\}} h(c)\left[c+\tau-c^{\circ}\right]dc, \\ \int_{\min\{\underline{c},c^{\circ}-\tau\}}^{\min\{\bar{c},c^{\circ}-\tau\}} h(c)\left[c^{\circ}-\tau-c\right]dc \end{array}\right\}. \end{aligned}$$

The first term in the maximization is the willingness to pay by the incumbent, the difference in return between having the production rights and a rival having them. The second term is the return to a rival owning the rights (a rival without rights gets profit equal to zero).

Observe that at $\tau=0$, the willingness to pay by the incumbent and a rival is the same and equal to

$$W^{No\_SD} = \int_{\underline{c}}^{\bar{c}} h(c)\left[c^{\circ}-c\right]dc, \text{ when } \tau=0,$$

the present value of the cost reduction. This expression follows from the fact that, with no switchover disruption, $\max\{\bar{c},c^{\circ}-\tau\}=\max\{c^{\circ}-\tau,\underline{c}\}=c^{\circ}$ (when $\tau=0$), and $\min\{\bar{c},c^{\circ}-\tau\}=\bar{c}$ and $\min\{\underline{c},c^{\circ}-\tau\}=\underline{c}$. Next observe that the willingness to pay $r^{No\_SD}$ of the rival strictly decreases in $\tau$. Finally, we differentiate $v^{No\_SD}-u^{No\_SD}$. Let us first note that

$$\frac{dv^{No\_SD}}{d\tau} = \int_{\underline{c}}^{\bar{c}} h(c)dc.$$

The derivative $du^{No\_SD}/d\tau$ is the sum of the following three terms,

$$-\frac{d\max\{c^{\circ}-\tau,\underline{c}\}}{d\tau}h(\max\{c^{\circ}-\tau,\underline{c}\})[\max\{c^{\circ}-\tau,\underline{c}\}+\tau-c^{\circ}],$$

and

$$\frac{d\max\{\bar{c}, c^\circ - \tau\}}{d\tau} h(\max\{\bar{c}, c^\circ - \tau\})[\max\{\bar{c}, c^\circ - \tau\} + \tau - c^\circ],$$

and finally

$$\int_{\max\{c^\circ-\tau,\underline{c}\}}^{\max\{\bar{c},c^\circ-\tau\}} h(c)dc.$$

The first two terms are zero (in each term, either the derivatives are zero, or if not, the rest of the expression is zero). Hence,

$$\frac{du^{No\_SD}}{d\tau} = \int_{\max\{c^\circ-\tau,\underline{c}\}}^{\max\{\bar{c},c^\circ-\tau\}} h(c)dc,$$

and hence

$$\frac{dv^{No\_SD}}{d\tau} - \frac{du^{No\_SD}}{d\tau} = \int_{\underline{c}}^{\bar{c}} h(c)dc - \int_{\max\{c^\circ-\tau,\underline{c}\}}^{\max\{\bar{c},c^\circ-\tau\}} h(c)dc.$$

This last derivative is strictly positive if $\tau < c^\circ - \underline{c}$ and zero for $\tau \geq c^\circ - \underline{c}$. Hence for $\tau > 0$, the valuation of the incumbent strictly exceeds that of the rival, and the valuation increases in $\tau$ up to the threshold. In summary, we have proved:

*Proposition 2.* Assume the Gilbert and Newbery setup applies, that demand is perfectly inelastic, and that there is no switchover disruption ($\bar{c} \leq c^\circ$).

(i) If $\tau > 0$, the incumbent has a higher valuation for the new innovation and will outbid the rival so $W^{No\_SD} = v^{No\_SD} - u^{No\_SD}$.

(ii) $W^{No\_SD}(\tau)$ strictly increases in $\tau$ for $\tau < c^\circ - \underline{c}$ and is constant above this point.

Part (i) of the proposition is a variant of Gilbert and Newbery's famous result that innovation is worth more to the incumbent than to a new entrant, and so the incumbent will preemptively patent before a rival. The incumbent will take into account that if it does not preemptively innovate and the entrant adopts instead, the incumbent will lose its monopoly rent. In contrast, the rivals have no rent to forgo if they don't innovate.

Part (ii) of the result is really an elaboration on part (i). The larger is $\tau$ the larger is the incentive of the incumbent to hold onto its monopoly rents, and so the more the incumbent is willing to pay for the innovation. This remains true until $\tau > c^\circ - \underline{c}$. When the friction is bigger than this threshold, a rival cannot displace the incumbent even when its costs have fallen to $\underline{c}$. So the incumbent will enjoy the full value of the friction $\tau$ whether or not the incumbent or a rival has the new technology, meaning changes in $\tau$ don't impact willingness to pay. Part (ii) of Proposition 2 flips the Arrow result because if there is a given underlying cost $F$ to create the innovation, the higher is monopoly power $\tau$, the more likely it is that the underlying valuation exceeds the innovation's cost.

**B. Adoption with Switchover Disruption**

The intuition embodied in Proposition 2 for how monopoly can raise the incentive to pay for innovation is well understood. The key point we want to make here is that this result depends heavily on the assumption that there is no switchover disruption. We will show that the presence of significant disruption overturns the results in Proposition 2.

In introducing disruption into the Gilbert and Newbery setup, we start off by noting that we must now allow for the complication that the incumbent might buy the technology and leave it idle, to prevent the rival from getting it. With no switchover disruption, $\bar{c} \leq c^\circ$, the incumbent would always use the new technology, if it owned the rights.

We require some additional notation. Define

$$\begin{aligned} H^{disrupt} &\equiv \int_{c^\circ}^{\bar{c}} h(c)dc, \\ H^{beyond} &\equiv \int_{\underline{c}}^{c^\circ} h(c)dc. \end{aligned}$$

$H^{disrupt}$ is the (weighted) duration of the switchover disruption, where the weight depends on the cost density and the discount factor, and $H^{beyond}$ is the (weighted) duration "beyond" the disruption, when cost is lower than its initial value $c^\circ$. Next, analogous to the terminology used in the previous subsection, let $v^{SD}$ be the value to the incumbent of obtaining the rights to the new technology for itself in the switchover disruption case. Let $u^{SD}$ be the value to the incumbent if a rival instead gets the rights, and finally let $r^{SD}$ be the value to a rival of obtaining the rights.

Before stating our formal results, it is useful to provide intuition by working through a simple example. For this example, we assume that during the disruption period, marginal cost is infinite, $\bar{c} = \infty$. After the disruption period is over, marginal cost declines to a constant $\underline{c} < (c^\circ - \tau)$. In this case, if the incumbent acquires and adopts the technology, it will have to completely shut down during the disruption phase, and will earn profits only during the "beyond" phase when the new technology is up and running,

$$v^{SD} = H^{beyond}\left(c^{\circ} - \underline{c}\right) + H^{beyond}\tau.$$

Note in this expression, we find it convenient to separate out two components of the return. The first is the flow profit $c^{\circ} - \underline{c}$ the incumbent gets from its cost advantage over rivals, once the new technology is up and running in the "beyond" period. The second is the flow profit it derives from its monopoly power advantage $\tau$ (e.g., its tariff or transportation advantage) it realizes when it gets back up and running. ($H^{beyond}$ is the present value weight placed on these later flow profits.) If instead, a rival firm procures the rights to the technology, the rival's value will be

$$r^{SD} = H^{beyond}\left(c^{\circ} - \underline{c}\right) - H^{beyond}\tau.$$

Note how $\tau$ adds to the profit that would go to the incumbent, while it subtracts from the profit that would go to a rival acquiring the new technology. Finally, if the rival procures the technology, then the incumbent will earn profit only during the disruption phase before the rival gets up and running,

$$u^{SD} = H^{disrupt}\tau.$$

Let $W^{SD}$ be the maximum of what the incumbent would be willing to pay and what a rival would pay, for the rights to the innovation. The incumbent's valuation is the difference between $v^{SD}$ and $u^{SD}$,

$$(10)\quad v^{SD} - u^{SD} = H^{beyond}\left(c^{\circ} - \underline{c}\right) - \left(H^{disrupt} - H^{beyond}\right)\tau.$$

A rival's bid is $r^{SD}$. It is immediate that if

$$\left(H^{disrupt} - H^{beyond}\right) > H^{beyond}$$

or equivalently

$$H^{disrupt} > 2H^{beyond},$$

a rival is willing to pay more than the incumbent. We can now see the first way that introducing switchover disruption changes things. In the Gilbert and Newbery setup covered in Proposition 2, where there is no switchover disruption, the incumbent always outbids the rivals. Here, if we put in disruption that is very large, a rival will outbid the incumbent. Intuitively, the disruption period creates a bigger opportunity cost for the incumbent than a rival.

The second way that switchover disruption changes things is in the comparative statics with market power $\tau$. For the case without switchover disruption covered in Proposition 2, the maximum willingness to pay for the innovation strictly *increases* in monopoly power $\tau$. Inspecting the equation for $v^{SD} - u^{SD}$ above (i.e., what the incumbent will pay), we see this increases in $\tau$ if disruption is small, $H^{disrupt} < H^{beyond}$, consistent with our earlier result. But if $H^{disrupt} > H^{beyond}$, the sign flips. That is, when switchover disruption is large, willingness to pay for the innovation strictly *declines* in market power $\tau$. In particular, if $H^{disrupt}$ is in the range of $H^{beyond}$ to $2H^{beyond}$, the incumbent outbids the rivals, but its bid is lower the higher $\tau$. And if $H^{disrupt}$ is above $2H^{beyond}$, rivals outbid the incumbent, but again this maximum bid is lower, the higher $\tau$.

If there is no discounting, the condition $H^{disrupt} > H^{beyond}$ for reversing Gilbert and Newbery reduces to the assumption that the disruption period is more than half of the unit time interval. With discounting, the disruption period need not be so long for the result to go through, since the disruption is borne up front. Thus, adding discounting magnifies the effect that we are emphasizing.[18]

The discussion so far has not addressed the issue that the incumbent might choose to procure the technology and leave it idle. The discussion also assumed a simple form of the technology. The formal results of this section apply for our more general technology and take into account the possibility that the technology may be left idle. Our first result is a local result for the case when market power $\tau$ is small. In this case, the new technology will never be acquired and left idle. We characterize the properties of the maximum valuation

[18] Note that there are other forces that act like discounting that will also magnify the impact of switchover disruptions. One example is if there is a small probability each "period" that the market disappears (for example, because of the development of a substitute product).

$W^{SD}$ for the rights to the new technology. These rights will be acquired if $W^{SD}$ exceeds the fixed cost $F$ of development of the new technology by the outside researcher. Thus, the larger is $W^{SD}$, the more likely the rights are acquired.

*Proposition 3.* Assume the Gilbert and Newbery setup applies, that demand is perfectly inelastic, and that there is a period of switchover disruption ($\bar{c} > c^{\circ}$). Suppose that $\tau$ is small (close enough to zero). Then if either the incumbent or a rival acquires the technology, it will be implemented and the switchover disruption incurred. The outcome will depend on the level of the disruption $H^{disrupt}$ as follows:

(i) If the disruption is small, $H^{disrupt} < H^{beyond}$, the maximum valuation $W^{SD}$ is the incumbent's valuation and it strictly *increases* in $\tau$.

(ii) If the disruption is intermediate, $H^{disrupt} \in (H^{beyond}, 2H^{beyond})$, the maximum valuation $W^{SD}$ continues to be the incumbent's valuation. However, $W^{SD}$ strictly *decreases* in $\tau$.

(iii) If the disruption is large, $H^{disrupt} > 2H^{beyond}$, the maximum valuation $W^{SD}$ is a rival's valuation, and it strictly *decreases* in $\tau$.

*Proof.* See the Appendix.

Our next result (Proposition 4) generalizes the two ways that big switchover costs overturn Gilbert and Newbery (which are parts (ii) and (iii) of Proposition 3) for $\tau$ that isn't small. For this wider range of $\tau$, for certain parameters it may be the case that the incumbent obtains the rights to the innovation but then leaves it idle. The following lemma shows that if this ever happens for any $\tau$, it happens for all higher $\tau$.

*Lemma 1.* Fix all the parameters of the model except for $\tau$. If there exists any $\tau$ where the incumbent obtains the new innovation rights but then idles it (and has a strict preference to do so), there is a cutoff $\hat{\tau} > 0$ such that for all $\tau < \hat{\tau}$, the incumbent does not obtain and idle the new innovation, but if $\tau > \hat{\tau}$ the incumbent does obtain the rights and idles it.

*Proof.* See the Appendix.

Define $\hat{\tau} = \infty$ in the event that there is no idling for any $\tau$. Proposition 4 requires an additional assumption.

*Assumption 1*: Assume that $f'(t)e^{\rho t}$ increases in $t$.

A few remarks about Assumption 1. We earlier assumed that $f'(t) < 0$. Now if the discount rate were $\rho = 0$, this assumption would be simply that $f'' > 0$, i.e., that $f$ is convex such as in the example in Figure 1. This would be a standard assumption in any kind of learning over time setup where the initial advances come in at a faster rate than later advances. If $\rho > 0$, we need more than convexity since the $e^{\rho t}$ term works against the assumption (note $f'(t) < 0$). We need $f$ to be convex *enough*. For example, if $f(t) = ke^{-\gamma t}$, then we need $\gamma > \rho$ for the assumption to hold. Assumption 1 directly implies that $h(c)$ decreases in $c$.[19]

With this setup, we can obtain our generalization of Proposition 3 to a wider range of $\tau$.

*Proposition 4.* As in Proposition 3, assume the Gilbert and Newbery setup applies, that demand is perfectly inelastic, and that there is a period of switchover disruption ($\bar{c} > c^{\circ}$). Assume further that Assumption 1 holds.

(i) If $H^{disrupt} > H^{beyond}$, $W^{SD}$ strictly decreases in $\tau$ for $\tau < \min\{c^{\circ} - \underline{c}, \hat{\tau}\}$.

(ii) If $H^{disrupt} > 2H^{beyond}$, the maximum valuation $W^{SD}$ is a rival's valuation for all $\tau < \min\{c^{\circ} - \underline{c}, \hat{\tau}\}$.

*Proof.* See the Appendix.

## VI. The Third Extension: Learning by Doing

The previous two sections considered critiques of Arrow's logic that competition increased adoption. In this section we consider whether our logic about switchover disruption's impact on adoption holds under different assumptions about how costs fall after adoption.

In the baseline model, if a firm adopts, then the path of its costs depends *only* on time. In particular, its costs do not depend on output, as they would if there was learning by doing (LBD). Since costs only depend on time, if the incumbent adopts and there is a large switchover disruption, that is, $\bar{c} > c^{\circ} + \tau$, then it is *always* best for the incumbent to drop out of the market until $\bar{c} = c^{\circ} + \tau$. So, the incumbent *always* loses sales.

If there is LBD, then a firm's production rate influences its costs. In this case, perhaps the firm will choose to produce when $\bar{c} > c^{\circ} + \tau$. If it produces, there is a current loss (since marginal cost exceeds price), but costs also come down faster. So, if there is LBD, perhaps an incumbent does not choose to reduce sales after adoption. If it did not reduce sales, then the effect we have introduced disappears.

In this section, we address this issue with a simple version of our model with learning by doing. We show that under general conditions our effect does not disappear.

Suppose for simplicity that demand is perfectly inelastic at $Q^D = 1$ and that there is no discounting. Suppose there are two cost levels after adoption, $\bar{c} > \underline{c}$, and that cost remains at the high level $\bar{c}$ until the firm attains a critical knowledge $K^*$. In general, knowledge comes from both raw time and production experience. Specifically, conditioned upon adopting the

[19] Recall that $h(c) \equiv e^{-\rho(1-G(c))}g(c) = -e^{-\rho t}f(t)^{-1}$, for $t$ solving $c = f(t)$.

new innovation at time $t = 0$, knowledge at time $t$ evolves according to

$$(11) \quad K(t) = \int_0^t [\lambda + \beta q(t)^\alpha] \, dt,$$

where $q(t)$ is the incumbent's production at time $t$. Assume $\alpha \in (0, 1)$. Specification (11) nests the pure time model that we formulated in Section II. To see this, if $\beta = 0$ and $\lambda > 0$, then at time $t^*$ defined by

$$K^* \equiv \lambda t^*,$$

the critical level of knowledge is obtained and cost drops from $\bar{c}$ to $\underline{c}$. This is the pure time model.

For the rest of this section, to stack things against us, we assume that time has no impact on learning, that is, $\lambda = 0$. We also assume that $\bar{c} > c^\circ + \tau$. So if the incumbent does adopt, if it ever wants to lower costs to $\underline{c}$, it will have to initially produce at a loss. We normalize $\beta = 1$ in (11). Finally, we assume

$$K^* < 1,$$

so that if the incumbent does produce the unit demand through the time interval, it obtains the required knowledge level before $t = 1$.

Suppose that the firm adopts and attains the critical knowledge at time $\hat{t}$. Assuming the curvature parameter $\alpha < 1$, and given no discounting, it is immediate that the firm should be smoothing production at a constant $q$ solving

$$K^* = \hat{t} q^\alpha$$

(where again we have normalized $\beta = 1$). Alternatively, if the firm chooses a constant production rate $q$, it achieves $K^*$ by $\hat{t}(q)$, where

$$\hat{t}(q) = \min \left\{ K^* q^{-\alpha}, 1 \right\},$$

and the bound at one covers the case where accumulated knowledge is insufficient by $t = 1$.

The incumbent chooses a learning-period production level $\bar{q}$ to solve

$$(12)\quad v = \max_{\bar{q}\leq 1} -\hat{t}(\bar{q})\bar{q}\left(\bar{c} - c^{\circ} - \tau\right) + \left(1 - \hat{t}(\bar{q})\right)\left(c^{\circ} + \tau - \underline{c}\right).$$

During the learning period, the incumbent sells $\bar{q} \leq 1$ units at a loss $(\bar{c} - c^{\circ} - \tau)$, and the balance of the unit market demand is met by the rivals. After the low cost $\underline{c}$ is attained, the incumbent takes the entire unit demand and begins to enjoy profit $c^{\circ} + \tau - \underline{c}$.

Our next result shows that if learning is "concave enough" ($\alpha < .703$ is sufficient), then there exists a range of $\bar{c}$ under which it is optimal for the incumbent to set an output level $\bar{q}$ during the learning phase that is positive but strictly less than one, i.e., it only partially meets the market demand during this phase. To set up the result, we need to introduce two functions of $\alpha$ that come up in the analysis:

$$(13)\quad \begin{aligned} M_1(\alpha) &\equiv \left(\frac{\alpha}{1-\alpha}\right)^{\alpha} \\ M_2(\alpha) &\equiv \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha} + \left(\frac{1-\alpha}{\alpha}\right)^{\alpha}. \end{aligned}$$

For a fixed $K^* < 1$, define $\hat{\alpha}$ by $M_1(\hat{\alpha}) \equiv M_2(\hat{\alpha})/K^*$. In the Appendix where we prove Proposition 5, we show there is a unique $\hat{\alpha} \in (.703, 1)$ satisfying this condition. Our result is:

*Proposition 5.* Fix $\alpha < \hat{\alpha}$ and define cutoffs $\bar{c}_1$ and $\bar{c}_2$ by

$$(14)\quad \begin{aligned} \frac{\bar{c}_1 - c^{\circ} - \tau}{c^{\circ} + \tau - \underline{c}} &\equiv M_1(\alpha)^{\frac{1}{\alpha}} \\ \frac{\bar{c}_2 - c^{\circ} - \tau}{c^{\circ} + \tau - \underline{c}} &\equiv M_2(\alpha)^{\frac{1}{\alpha}}\left(K^*\right)^{-\frac{1}{\alpha}}. \end{aligned}$$

The cutoffs satisfy $\bar{c}_2 > \bar{c}_1$ and $\bar{c}_1 > c^{\circ} + \tau$. In the solution to problem (12), if $\bar{c} \in (\bar{c}_1, \bar{c}_2)$, then output during the learning period is strictly positive but less than one,

$$(15)\quad \bar{q} = \frac{\alpha}{1-\alpha}\frac{c^{\circ} + \tau - \underline{c}}{\bar{c} - c^{\circ} - \tau} < 1.$$

If instead $\bar{c} < \bar{c}_1$, then $\bar{q} = 1$ during the learning period. If $\bar{c} > \bar{c}_2$, then if the firm were to adopt, $\bar{q} = 0$ for all $t$ and knowledge $K^*$ is never attained.

*Proof.* See the Appendix.

As before, define $W(\tau) = v(\tau) - v^{\circ}(\tau) - F$ to be the net value of adopting the new technology. Our result is

*Proposition 6.* Assume $\alpha < \hat{\alpha}$. If $\bar{c} < \bar{c}_1$, then $W'(\tau) = 0$. If $\bar{c} > \bar{c}_1$, then $W'(\tau) < 0$.

*Proof.* The slope equals

$$\begin{aligned}\frac{dW}{d\tau} &= \frac{dv}{d\tau} - \frac{dv^{\circ}}{d\tau} \\ &= \left[\hat{t}(\bar{q})\bar{q} + \left(1 - \hat{t}(\bar{q})\right)\right] - 1.\end{aligned}$$

The bracketed term is the slope of $v$ obtained from (12) using the envelope theorem. The impact of a change in $\tau$ is simply the average output. If $\bar{c} > \bar{c}_1$, then from Proposition 5, $\bar{q} < 1$, and average output under adoption is strictly less than one, implying $W'(\tau) < 0$. If $\bar{c} < \bar{c}_1$, average output under adoption is one, and $W'(\tau) = 0$.

Proposition 6 shows that our basic insight continues to hold if we cast the disruption period as learning by doing. If $\bar{c}$ is large enough so that losses during the learning period are big enough, an incumbent that is adopting will contract its sales below the full market level of one unit. The bigger is $\tau$, the more costly these lost sales, and the less the return to adoption.[20]

## VII. More Extensions

In this section, we briefly discuss some straightforward extensions of the model. These extensions show how the model can be interpreted more broadly and how the effects we talk about can be magnified.

### A. Incumbent Faces Rivals in Many Markets (i.e., Variation in $\tau$)

In the analysis above where there is a large switchover disruption, the incumbent loses its entire market for a period of time. But in more general models, the incumbent need not lose

[20] One important thing to note is that in the extreme case where $\alpha = 1$ so there are no diminishing returns to learning, the incumbent goes to the corner upon adopting and sets either $\bar{q} = 1$ or $\bar{q} = 0$. Now it will never choose to adopt and set $\bar{q} = 0$. So if the turn to adoption is positive, then the return does not vary with $\tau$, because the incumbent does not lose sales if it adopts. It is crucial for our result that there be diminishing returns in learning, so that the incumbent smooths out its learning and loses some sales. Another thing worth noting is even though an incumbent with higher $\tau$ is less likely to adopt, given that it does adopt, we can see from (15) that it will operate at a higher output $\bar{q}$ during the learning period and hence attain the required knowledge $K^*$ faster.

its entire market in order for the effect we are talking about to go through.[21] We illustrate this here by allowing the incumbent's advantage over rivals to be big in some markets and small in others. In this setup, even during the switchover disruption when the incumbent has high costs, it will nonetheless continue to sell to consumers over whom it has high monopoly power. The incumbent will lose mobile consumers during the disruption, and on account of these mobile consumers our results will go through.

So now assume that there are multiple markets that differ by $\tau$, in particular, let $\tau \in [0, \bar{\tau}]$. To keep things simple, assume demand is perfectly inelastic in each market and that the level of demand in each market differs by a scaler weight $a(\tau)$. Furthermore, assume that firms can perfectly discriminate between the markets, being able to offer a distinct price $p(\tau)$ to each market $\tau$. This simplifies things considerably, as we can determine the Bertrand equilibrium in each market separately.

This structure can be given several interpretations. In terms of the tariff example mentioned earlier, it may simply be the case that different consumers face different tariffs. Or we can interpret this as heterogeneity in transport costs in a spatial context with a Hotelling-like structure. We can put the incumbent in the center of a country. Buyers located in the center of the country have high $\tau$ because in addition to paying any tariff, they have to incur transportation costs to ship imports inland. Buyers located on the coast have lower $\tau$.

Let $W_{many\text{-}markets}$ be the net return to innovation in this new *many-markets* model. Given that the equilibrium can be determined in each $\tau$ market separately, we can use equation (5) of Section III to determine the return to innovation $W(\tau)$ in each $\tau$ market and then integrate over $\tau$ to obtain the net return over all markets,

$$(16) \quad W_{many\text{-}markets} = \int_0^{\bar{\tau}} a(\tau) W(\tau) d\tau.$$

Since we have assumed perfectly inelastic demand here, the first term in the slope of $W(\tau)$ in equation (6) (the Arrow output effect) is zero. It is immediate then that $W'(\tau) \leq 0$ and that the inequality is strict for those $\tau$ markets where $\bar{c} > c^{\circ} + \tau$, i.e., where the incumbent is initially out of the market just after adoption. It is then clear that an upward shift in the distribution of $\tau$ (in the sense of first-order stochastic dominance) strictly decreases

[21] Another extension (besides the one we consider below) would be for the incumbent, upon adoption, to be able to produce only a certain fraction $y$ of its pre-adoption output for a period of time. We could assume during this period it produced at marginal cost $\bar{c}$ (or $\underline{c}$), and that once the period is over, it produced at $\underline{c}$.

willingness to pay and our result goes through. We also see that in the very high $\tau$ markets (where $\bar{c} < c^{\circ} + \tau$), the incumbent retains its sales just after adoption, so the incumbent's aggregate output never goes all the way to zero.

**B. Consumer Dynamics**

Our consumer model features no dynamics. Fixing the prices of the incumbent and all rivals, the quantity sold by the incumbent is independent of history. A large literature emphasizes the importance of dynamics on the consumer side. Consumers may bear "switching costs" when they shift from one provider to a second provider. If the consumer goes ahead and makes such a switch, the first provider might have a difficult time getting the consumer back. See Klemperer (1995) for a survey of this literature.

If we introduce these kinds of dynamics on the consumer side, the effects we are isolating here are magnified. We make our point with a stylized example, but our point is more general. Suppose that when consumers purchase from a rival, there is some probability they will never come back to the incumbent. Specifically, demand available to the incumbent decays at rate $\delta$ when demand is met by a rival firm. In this case we can rewrite the incumbent's willingness to pay (10) for the innovation in the example at the close of Section V as

$$W^{SD} = e^{-\delta H^{disrupt}} H^{beyond} \left(c^{\circ} + \tau - \underline{c}\right) - H^{disrupt}\tau.$$

This is the same as (10), except the first term now includes a decay factor for consumers lost over the course of the disruption interval (which has length $H^{disrupt}$). In the original analysis, $\delta = 0$ is implicitly assumed. The comparative static that $W^{SD}$ decreases in $\tau$ now holds if

$$e^{-\delta H^{disrupt}} H^{beyond} < H^{disrupt}.$$

For any positive disruption interval $H^{disrupt}$, the above condition will hold for large enough consumer decay $\delta$.

**C. Uncertainty**

The model is set up with a deterministic cost structure. Often there is a great deal of uncertainty in the adoption of a new technology, and this reinforces our point. It may be that a new technology is worse than the existing one, even in the long run, but the only way to find out is to try it. Moreover, once a firm tries it, it may be stuck with it, at least for a substantial period of time. For example, the adoption of a new baggage handling system in the Denver airport turned out to be a mistake, but it took ten years before the airport abandoned it.

We can capture this with a simple relabeling. Suppose that the model is a static one, in which there is uncertainty about the realization $c$ of a new technology. Assume that if the cost draw ends up $c > c^{\circ}$, the adopting firm is stuck with it—that is, the cost of reverting to the previous technology is prohibitively high. If we simply let $h(c)$ be the density of the cost draw $c$ for the new technology, the model is formally identical to the model studied, and all of our results go through.

## VIII. Conclusion

Overall, while the Arrow theory provides a possible explanation of why monopolies are observed to be sluggish innovators, it does not seem to fit the evidence particularly well. Indeed, monopolists tend to be conservative in a great many ways. And indeed, this makes sense: if you have a good thing going, you do not want to rock the boat. The one thing a monopolist fears most is the loss of monopoly. This is exactly the driving force that explains why switchover disruptions can be so important: a competitor has little to fear from a disruption as they are earning little to begin with. A firm with a lucrative monopoly is well advised not to jeopardize it by adopting a technology that may, in the short run at least, threaten its lucrative position.

# Appendix

*Proof of Proposition 3*

Suppose as assumed in Proposition 3 that $\bar{c} > c^{\circ}$ and $\tau \in (0, c^{\circ} - \underline{c})$. To do the analysis, we need to derive four different returns.

*First Return:* $v^{SD}$

This is the return to the incumbent from adopting the technology,

$$(17)\quad v^{SD} = \int_{\underline{c}}^{\min\{c^{\circ}+\tau,\bar{c}\}} h(c)\left[c^{\circ} + \tau - c\right] dc,$$

where if $\min\{c^{\circ} + \tau, \bar{c}\} = \bar{c}$, the incumbent is always the low-cost producer.

*Second Return:* $i^{SD}$

This is the return if the incumbent acquires the rights to the new technology but leaves it idle,

$$i^{SD} = \int_{\underline{c}}^{\bar{c}} h(c)\tau dc,$$

since the markup is $\tau$ and demand is unity.

*Third Return:* $u^{SD}$

This is the return to the incumbent of not acquiring the technology (so that it ends up in the hands of a rival),

$$(18)\quad u^{SD} = \int_{c^{\circ}}^{\bar{c}} h(c)\tau dc + \int_{c^{\circ}-\tau}^{c^{\circ}} h(c)\left[c + \tau - c^{\circ}\right] dc.$$

The first term is the return over the disruption interval, that is, the time before the adopting rival's cost (not including the friction $\tau$) has fallen to $c^{\circ}$, that is, the interval $[c^{\circ}, \bar{c}]$. The adopting rival begins with total cost $\bar{c} + \tau$ (which satisfies $\bar{c} + \tau > c^{\circ} + \tau > c^{\circ}$), but since there are other rivals (we assumed multiple rivals) with cost $c^{\circ} + \tau$, the incumbent's limit price is $c^{\circ} + \tau$ and its markup $\tau$. The second term is the return after the disruption interval. In this period, the adopting rival has a cost $c + \tau < c^{\circ} + \tau$. For the first part of this period, the incumbent's cost $c^{\circ}$ remains lower than $c + \tau$, during which period the equilibrium price is $c + \tau$. Eventually, since $\underline{c} < c^{\circ}$ and since $\tau < c^{\circ} - \underline{c}$ by assumption (since $\tau$ is assumed "small"), a point is reached (i.e., $c + \tau = c^{\circ}$) where the rival that adopts is the lowest-cost producer (including the friction $\tau$) and the incumbent's profit is zero from that point on.

*Fourth Return:* $r^{SD}$

The return to a rival of adopting the technology is

$$r^{SD} = \int_{\underline{c}}^{c^\circ-\tau} h(c)\left[c^\circ - \tau - c\right] dc,$$

since its limit price is $c^\circ$ and its marginal cost is $c+\tau$.

Willingness to pay in the switchover disruption case is given by

$$W^{SD} = \max\left\{v^{SD} - u^{SD}, i^{SD} - u^{SD}, r^{SD}\right\}.$$

We begin by noting that for $\tau$ close to zero, it is immediate that $v^{SD} > i^{SD}$. This proves that for small $\tau$, idling never occurs in equilibrium, as claimed. It remains to compare $v^{SD} - u^{SD}$ and $r^{SD}$. Note at $\tau = 0$ they are equal. Let us differentiate the difference, $v^{SD} - u^{SD}$, with respect to $\tau$. First, we have that

$$\frac{dv^{SD}}{d\tau} = \frac{d\min\left\{c^\circ+\tau, \bar{c}\right\}}{d\tau} h(\min\left\{c^\circ+\tau, \bar{c}\right\})[c^\circ + \tau - \min\left\{c^\circ+\tau, \bar{c}\right\}] + \int_{\underline{c}}^{\min\{c^\circ+\tau, \bar{c}\}} h(c)dc,$$

where note that the first term is zero. Hence, we have that

$$(19) \quad \frac{dv^{SD}}{d\tau} - \frac{du^{SD}}{d\tau} = \int_{\underline{c}}^{\min\{c^\circ+\tau, \bar{c}\}} h(c)dc - \int_{c^\circ-\tau}^{\bar{c}} h(c)dc,$$

and note that, at $\tau = 0$, $dv^{SD}/d\tau - du^{SD}/d\tau = H^{beyond} - H^{disrupt}$. Next, we have

$$(20) \quad \frac{dr^{SD}}{d\tau} = -\int_{\underline{c}}^{c^\circ-\tau} h(c)dc$$

and note that, at $\tau = 0$, $dr^{SD}/d\tau = -H^{beyond}$.

If $H^{beyond} > H^{disrupt}$, then for $\tau = 0$, (19) is positive and greater than (20). This implies that the incumbent has the highest willingness to pay for small $\tau$. Thus, $W^{SD} = v^{SD} - u^{SD}$, and this is strictly increasing for small $\tau$, proving (i).

If $H^{disrupt} \in (H^{beyond}, 2H^{beyond})$, then (19) is strictly negative but still greater than (20).

Thus, $W^{SD} = v^{SD} - u^{SD}$ and is strictly decreasing for small $\tau$, proving (ii).

If $H^{disrupt} > 2H^{beyond}$, then (19) is strictly less than (20). So a rival has the highest willingness to pay. So $W^{SD} = r^{SD}$, which is strictly decreasing, proving (iii).

*Proof of Lemma 1*

Following the notation and formulas found in the proof of Proposition 3, we have

$$\begin{aligned} \frac{dv^{SD}}{d\tau} - \frac{du^{SD}}{d\tau} &= \int_{\underline{c}}^{\min\{c^\circ+\tau,\bar{c}\}} h(c)dc - \int_{\max\{c^\circ-\tau,\underline{c}\}}^{\bar{c}} h(c)dc \\ \frac{di^{SD}}{d\tau} - \frac{du^{SD}}{d\tau} &= \int_{\underline{c}}^{\bar{c}} h(c)dc - \int_{\max\{c^\circ-\tau,\underline{c}\}}^{\bar{c}} h(c)dc \\ \frac{dr^{SD}}{d\tau} &= -\int_{\underline{c}}^{\max\{c^\circ-\tau,\underline{c}\}} h(c)dc. \end{aligned}$$

Note that at $\tau = 0$,$i^{SD} - u^{SD} = 0$, while $v^{SD} - u^{SD} = r^{SD} > 0$. Next note for $\tau \in (0, \underline{c} - c^\circ)$ that $i^{SD} - u^{SD}$ is strictly increasing while $r^{SD}$ is strictly decreasing. For $\tau > \underline{c} - c^\circ$, $i^{SD} - u^{SD}$ is weakly increasing while $r^{SD}$ is flat. Hence, if there is ever a point $\tau$ where $i^{SD} - u^{SD} > r^{SD}$, there is a unique cutoff $\tau'$ where $i^{SD} - u^{SD} = r^{SD}$, and $i^{SD} - u^{SD} < r^{SD}$ if and only if $\tau < \tau'$.

If $c^\circ + \tau < \bar{c}$, then the slope of $i^{SD} - u^{SD}$ is strictly greater than the slope of $v^{SD} - u^{SD}$ and otherwise the slope is equal. Hence, if there is ever a point $\tau$ where $i^{SD} - u^{SD} > v^{SD} - u^{SD}$, there is a unique cutoff $\tau''$ where $i^{SD} - u^{SD} = v^{SD} - u^{SD}$, and $i^{SD} - u^{SD} < v^{SD} - u^{SD}$ if and only if $\tau < \tau''$.

If the points $\tau'$ and $\tau''$ don't exist, then for no $\tau$ is there a strict preference to idle. If both exist, then let $\hat{\tau} \equiv \max\{\tau', \tau''\}$.

*Proof of Proposition 4*

For $\tau < \min\{c^\circ - \underline{c}, \hat{\tau}\}$, by the definition of $\hat{\tau}$, the incumbent is not idling the technology. Hence, the formula (19) is valid for $\tau$ in this range. Differentiating again yields

$$\begin{aligned} \frac{d^2v^{SD}}{d\tau^2} - \frac{d^2u^{SD}}{d\tau^2} &= h(c^\circ + \tau) - h(c^\circ - \tau), \text{ if } c^\circ + \tau < \bar{c}, \\ &= -h(c^\circ - \tau), \text{ if } c^\circ + \tau > \bar{c} \end{aligned}$$

Assumption 1 implies $h' < 0$, so the above is strictly negative. Since $H^{disrupt} > H^{beyond}$, $v^{SD} - u^{SD}$ is strictly decreasing for small $\tau$. Since the function is strictly concave, it is then strictly decreasing for all $\tau \in (0, c^\circ - \underline{c})$. Next note from (20) that $r^{SD}$ is strictly decreasing. Now $W^{SD} \equiv \max\{v^{SD} - u^{SD}, r^{SD}\}$, where $v^{SD} - u^{SD}$ and $r^{SD}$ are both decreasing functions of $\tau$. The maximum of decreasing functions is a decreasing function, proving (i). Next observe from differentiating (20) with respect to $\tau$ that $r^{SD}$ is (weakly) convex. If $H^{disrupt} > 2H^{beyond}$, the slope of $r^{SD}$ at $\tau = 0$ is strictly greater than the slope of $v^{SD} - u^{SD}$. Since $r^{SD}$ is convex and $v^{SD} - u^{SD}$ is concave and since $v^{SD} - u^{SD} = r^{SD}$ at $\tau = 0$, $r^{SD} > v^{SD} - u^{SD}$ for $\tau \in (0, \min\{c^\circ - \underline{c}, \hat{\tau}\})$ as claimed.

*Proof of Proposition 5*

We begin by plotting the functions $M_1(\alpha)$ and $M_2(\alpha)$ in Appendix Figure 1. It is immediate that $M_1(\alpha) \leq 1$ for $\alpha \in (0, \frac{1}{2}]$, that $M_1(\alpha) > 1$, $M_1'(\alpha) > 0$ for $\alpha \in [\frac{1}{2}, 1)$, and that $\lim_{\alpha \to 1} M_1(\alpha) = \infty$. It is immediate that $M_2(\alpha) > 1$ for $\alpha \in [\frac{1}{2}, 1)$. In the figure it is readily apparent that $M_2'(\alpha) < 0$, for $\alpha > \frac{1}{2}$ and $\lim_{\alpha \to 1} M(\alpha) = 1$. Note that the $M_1$ and $M_2$ functions intersect at a point slightly above $\alpha = .703$. Given these facts, it follows that for $K^* < 1$, there exists a unique $\hat{\alpha} \in (.703, 1)$ solving

$$M_1(\hat{\alpha}) = \frac{1}{K^*} M_2(\hat{\alpha}),$$

so that for $\alpha < \hat{\alpha}$, $M_1(\alpha) < \frac{1}{K^*} M_2(\alpha)$. Given the definitions (14) of the cutoffs $\bar{c}_1$ and $\bar{c}_2$, it follows that $\bar{c}_2 > \bar{c}_1$ and $\bar{c}_1 > c^\circ + \tau$.

Recall from the text that

$$\hat{t}(q) = \min\left\{K^* q^{-\alpha}, 1\right\}$$

and the incumbent chooses a learning-period production level $q$ to solve

$$\text{(21)} \quad v = \max_{q \leq 1} -\hat{t}(q) q \left(\bar{c} - c^\circ - \tau\right) + \left(1 - \hat{t}(q)\right)\left(c^\circ + \tau - \underline{c}\right).$$

Let $\tilde{v}(q)$ be the value at a given $q$. The slope equals

$$\tilde{v}'(q) = -\left(1 - \alpha\right) K^* q^{-\alpha} \left(\bar{c} - c^\circ - \tau\right) + \alpha K^* q^{-\alpha - 1} \left(c^\circ + \tau - \underline{c}\right).$$

This formula applies when $q$ is in the interval $q \in [K^*, 1]$. For $q < K^*$, the firm never learns, so the second term of (21) drops out. Let $\tilde{q}(\bar{c})$ solve $\tilde{v}'(q) = 0$,

$$\tilde{q}(\bar{c}) = \frac{\alpha}{1 - \alpha} \frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}.$$

It is straightforward to prove that for $q \in [K^*, 1]$, $\tilde{v}'(q) \geq 0$ implies $\tilde{v}''(q) < 0$. Hence, if $\tilde{q}(\bar{c}) \in [K^*, 1]$, $\tilde{q}(\bar{c})$ must be the unique maximizer of $\tilde{v}(q)$ for $q$ in the interval $[K^*, 1]$.

Suppose first that $\bar{c} = \bar{c}_2$. Then

$$\begin{aligned}\tilde{q}(\bar{c}_2) &= \frac{\alpha}{1-\alpha}\frac{c^\circ + \tau - \underline{c}}{\bar{c}_2 - c^\circ - \tau} \\ &= \frac{M_1^{\frac{1}{\alpha}}}{M_2(\alpha)^{\frac{1}{\alpha}}\,(K^*)^{-\frac{1}{\alpha}}} < 1,\end{aligned}$$

where we use the definitions of $\bar{c}_2$ and $M_1(\alpha)$ and $M_1(\alpha)$ and that $M_1(\alpha) < \frac{1}{K^*}M_2(\alpha)$, for $\alpha < \hat{\alpha}$. We can rewrite this as

$$\tilde{q}(\bar{c}_2)^\alpha = \frac{M_1}{M_2}K^*.$$

Since $\alpha < \hat{\alpha}$, $M_1 > M_2$. Since $\alpha < 1$ and since $K^* < 1$, it follows that $\tilde{q}(\bar{c}_2) > K^*$. Hence, $\tilde{q}(\bar{c}_2) \in (K^*, 1)$, and so it is the unique maximizer of $\tilde{v}(q)$ over the interval $[K^*, 1]$. The maximized value equals

$$\begin{aligned}\tilde{v}(\tilde{q}) &= -K^*\tilde{q}^{-\alpha}\tilde{q}\,(\bar{c} - c^\circ - \tau) + \left(1 - K^*\tilde{q}^{-\alpha}\right)(c^\circ + \tau - \underline{c}) \\ &= -K^*\left[\frac{\alpha}{1-\alpha}\frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}\right]^{1-\alpha}(\bar{c} - c^\circ - \tau) \\ &\quad + \left(1 - K^*\left[\frac{\alpha}{1-\alpha}\frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}\right]^{-\alpha}\right)(c^\circ + \tau - \underline{c}),\end{aligned}$$

so

$$\begin{aligned}\frac{\tilde{v}(\tilde{q})}{(c^\circ + \tau - \underline{c})} &= -K^*\left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\left(\frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}\right)^{-\alpha} \\ &\quad +1 - K^*\left(\frac{1-\alpha}{\alpha}\right)^{\alpha}\left(\frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}\right)^{-\alpha} \\ &= 1 - K^*M_2(\alpha)\left(\frac{c^\circ + \tau - \underline{c}}{\bar{c} - c^\circ - \tau}\right)^{-\alpha} = 0, \text{ at } \bar{c} = \bar{c}_2.\end{aligned}$$

The last line follows from the definition of $\bar{c}_2$. At this point it is convenient to write $\tilde{v}(q, \bar{c})$ as an explicit function of $\bar{c}$. We have shown that at $\bar{c} = \bar{c}_2$, $\tilde{v}(\tilde{q}(\bar{c}_2), \bar{c}_2) = 0$. Since $\tilde{v}(q, \bar{c})$ strictly decreases in $\bar{c}$, for $q > 0$, it is immediate that $\tilde{v}(\tilde{q}(\bar{c}), \bar{c}) < 0$, for $\bar{c} > \bar{c}_2$. Hence, the optimal policy (given adoption) for $\bar{c} > \bar{c}_2$ is to set $\bar{q} = 0$ and sustain no losses during the learning period and never learn. For $\bar{c} < \bar{c}_2$, it is immediate that the optimal policy is to set $\bar{q}(\bar{c}) = \min\{\tilde{q}(\bar{c}), 1\}$. Now $\tilde{q}(\bar{c})$ monotonically decreases in $\bar{c}$. By the definition of $\bar{c}_1$, $\tilde{q}(\bar{c}_1) = 1$. So for $\bar{c} \in (\bar{c}_1, \bar{c}_2)$, $0 < \bar{q}(\bar{c}) < 1$, as claimed.

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Figure 1
An Example of a Cost Structure with Switchover Disruption

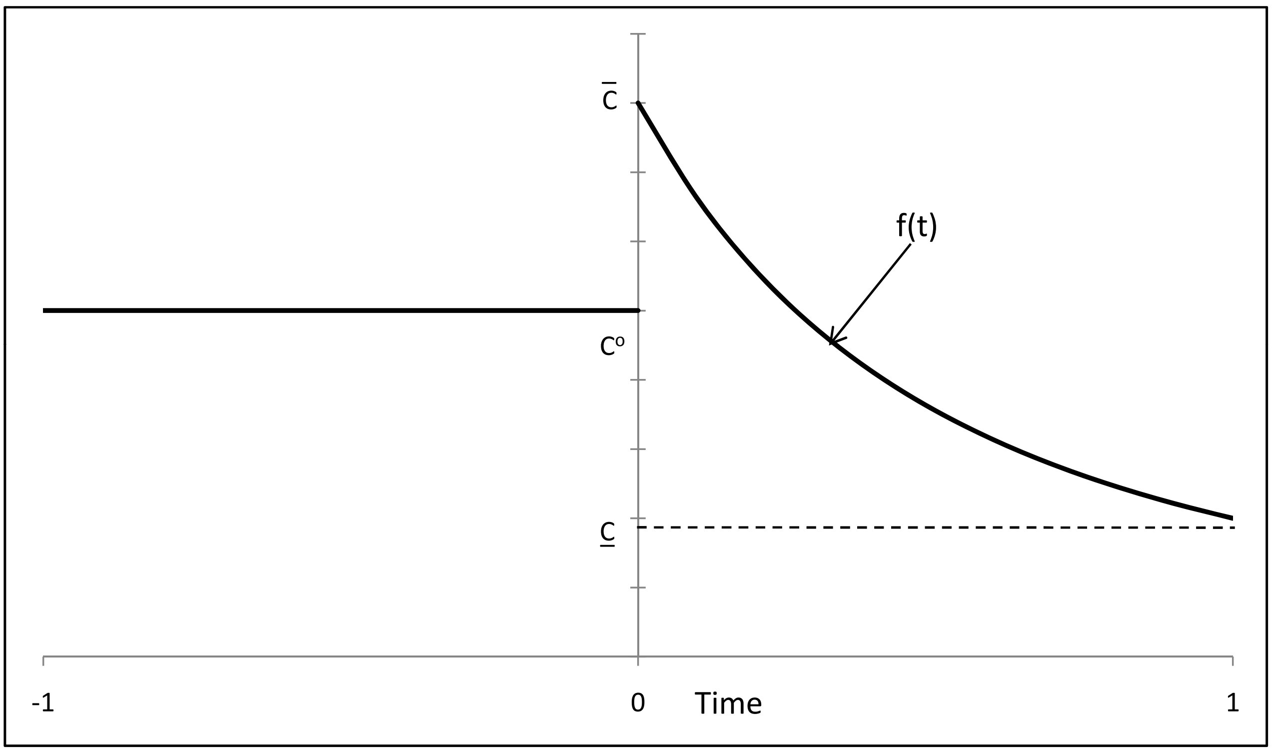


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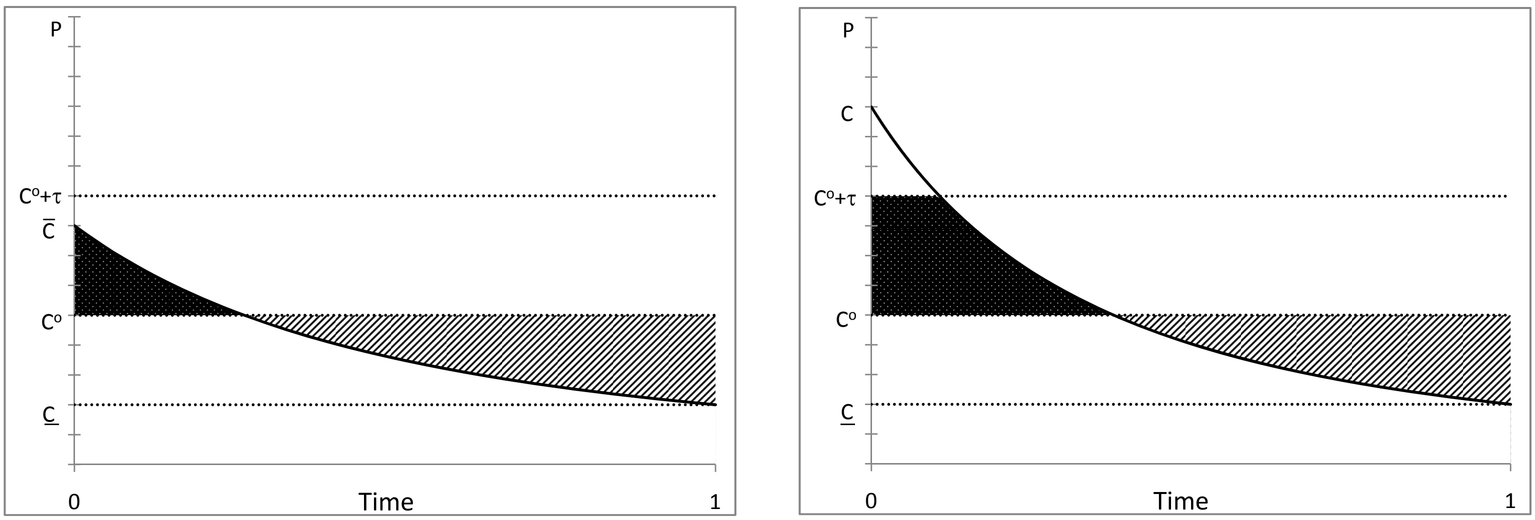
Figure 2
The Incentives to Adopt with Small and Large Switchover Disruption




(a) Small Switchover Disruption

(b) Large Switchover Disruption

Appendix Figure 1